Analyzing Average Age of Information in CRDSA Protocol with Access-Banned Policy

Ziru Wang, Boming Cheng, Zheng Yang, and Jie Zeng(✉)

School of Cyberspace Science and Technology, Beijing Institute of Technology,
Beijing 100081, China
{3220221464,3120211381,3120231286,zengjie}@bit.edu.cn

Abstract. This paper focuses on the analysis of the average age of information (AAoI) of the Contention Resolution Diversity Slotted ALOHA (CRDSA) protocol based on the access-banned policy in massive machine-type communication (mMTC) scenarios. The CRDSA system is modeled as a bipartite graph, and graph theory methods are used to analyze the system performance. At the same time, a comprehensive formula for calculating the packet recovery rate (PRR) in the CRDSA system is derived, considering the spectral characteristics of the bipartite graph. This formula can quantitatively evaluate the system's ability to successfully decode transmitted data packets. Based on this, the age of information (AoI) in the CRDSA system based on the access-banned policy is studied. The sparse access model and the sampling method at the beginning of each frame are considered, and the expression of the AAoI of the whole system is given. The analysis process considers the probabilities of successful and failed decoding and the impact of decoding on delay, thus gaining a deep understanding of the freshness of information in the CRDSA system. The research results of this paper are of great significance for optimizing the design of the CRDSA protocol based on the access-banned policy. The research results can improve the reliability and efficiency of system performance in mMTC scenarios.

Keywords: Massive machine-type communication · Access-banned policy · CRDSA protocol · Age of information

1 Introduction

The fifth generation (5G) communication technology provides three service areas for the Internet of Things(IoT) [1], among which massive machine-type commu-

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This work was supported by the Fundamental Research Funds for the Central Universities, the National Key Research and Development Program under Grant 308, the National Natural Science Foundation of China under grant 62001264, and the Beijing Institute of Technology Research Fund Program for Young Scholars.

F. Gao et al. (Eds.): Chinacom 2023, LNICST 590, pp. 233–246, 2024.
https://doi.org/10.1007/978-3-031-67162-3_15

nication (mMTC) is suitable for scenarios involving sensing and data collection, requiring efficient, reliable and secure wireless communication protocols. ALOHA protocol is one of the earliest wireless communication protocols, where nodes send data directly and retransmit after collisions, simple but inefficient. Frame Slotted ALOHA (FSA) protocol [2] is an improvement of ALOHA protocol, dividing time into slots, where nodes can only send data at the beginning of slots, reducing collisions and improving efficiency. FSA protocol is more suitable for mMTC application scenarios.

In the context of IoT, evaluating and improving data freshness is a crucial issue. In certain IoT applications, such as wireless sensor networks, sensor nodes need to send monitored data to the information fusion node promptly, which demands high data freshness. To quantify the freshness of data packets collected by user equipment (UE) in mMTC scenarios [3], researchers have proposed a metric called Age of Information [4] (AoI). AoI measures the time interval between two update packets sent by the UE, and the average AoI [5] (AAoI) reflects the system's freshness. AoI differs from other traditional metrics like latency.

To enhance AoI performance, researchers have proposed works based on both slot-based ALOHA and frame-based ALOHA protocols [6–9]. Slot-based ALOHA works analyze the impact of arrival rate and packet error rate on system AoI and propose age-related random access strategies. Steady-state analysis is performed, and access parameters are optimized. Frame-based ALOHA works involve threshold ALOHA protocol analysis [6], obtaining the expression of AoI and optimizing access parameters. Yu et al. [7] analyzed the AoI of four versions of FSA protocol (synchronous and asynchronous FSA protocol, with and without retransmission mechanism), and derived the lower bound and exact expression of AoI, as well as the optimal slot length [8]. Fixed threshold and adaptive threshold slot-based ALOHA protocols are compared, and a lower bound is provided. Additionally, coded slotted ALOHA (CSA) protocol combined with threshold strategy is adopted to improve system AAoI performance. An access-banned policy [9] with a threshold strategy is proposed to enhance the AAoI performance of CSA protocol, extending it to dense and sparse access models and two sampling methods.

The main contributions of this paper can be summarized as follows:

- Bipartite graph modeling and performance analysis: The paper proposes a approach to model the CRDSA system as a bipartite graph. By dividing the system into user nodes and slot nodes, connected by edges representing packet replicas, the graph theory methods are applied to analyze the system's performance. This modeling framework provides insights into the behavior and dynamics of CRDSA systems.
- Packet recovery rate (PRR) formula and analysis: The paper derives a comprehensive formula for calculating the packet recovery rate in CRDSA systems. By considering the spectral properties of the bipartite graph, including the spectral radius and largest eigenvalue, the PRR formula incorporates the expected number of clean slot nodes and active user nodes. This formula enables quantitative evaluation of the system's ability to successfully decode transmitted packets.

- Analysis of AoI in CRDSA with Access-Banned policy: The paper investigates the Age of Information AoI in CRDSA systems under access prohibition, considering the sparse access model. It presents an expression for the AAoI of each user and the entire system. The analysis takes into account the probabilities of successful and unsuccessful decoding, as well as the impact of decoding on AoI. The derived AAoI expression provides insights into the information freshness in CRDSA systems.

This paper is organized as follows. Section 2 introduces the system model and the decoding process of the uplink random access system. Section 3 proposes the access-banned policy and the frame-based CRDSA protocol to minimize AAoI, and analyzes their performance using a bipartite graph model. Section 4 presents and discusses the numerical simulation results. Section 5 concludes the paper.

2 System Model

We consider a synchronous slot-based uplink random access system [10] Fig. 1. In this system, each MAC frame is divided into M slots, with M representing the frame length. The system maintains frame and slot synchronization, and each UE is allowed to send at most one packet within a slot. However, collisions are prone to occur in this system. As a result, the base station receives a mixture of signals from the UEs in each slot. Based on the power of the received signal, the BS can classify the situations into three categories [9]:

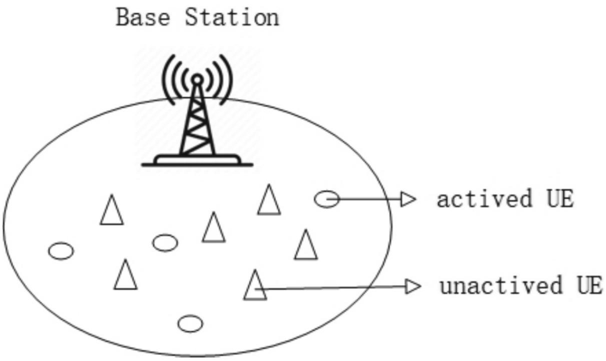

Fig. 1. System model

a) Idle: No data transmission from any UE in the slot. b) Singleton: Only one UE sends data, making it a singleton slot. c) Collision: More than one UE sends data, causing signal interference.

We assume that the BS can correctly decode the data in a singleton slot if the received signal power exceeds a specific threshold. In the case of a collision, the

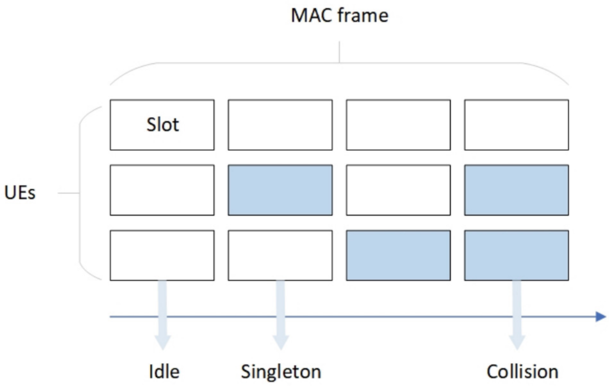

Fig. 2. BS receive situations

BS applies successive interference cancellation (SIC) to recover the transmitted data after the MAC frame is finished (Fig. 2).

We suppose that there are N UEs that may access the system, and each UE has a unique ID in the uplink system. We use the subscript i to indicate a specific UE as U_i.

In the k-th frame, we denote the number of active UEs, access-allowed UEs, and successfully decoded UEs as $N_a^{(k)}$, $N_t^{(k)}$, and $N_R^{(k)}$ respectively

$$\mathbb{E}[N_a] = \lim_{K\to\infty} \frac{1}{K} \sum_{k=1}^{K} N_a^{(k)} \tag{1}$$

$$\mathbb{E}[N_t] = \lim_{K\to\infty} \frac{1}{K} \sum_{k=1}^{K} N_t^{(k)} \tag{2}$$

$$\mathbb{E}[N_R] = \lim_{K\to\infty} \frac{1}{K} \sum_{k=1}^{K} N_R^{(k)} \tag{3}$$

Due to the sparsity of mMTC [11], consider using the sparse access model, where each UE is activated with a small probability p_a at the beginning of each frame. In this case, the average number of active UEs is $\mathbb{E}[N_a] = p_a N$. Each UE performs the sampling process at the beginning of the frame: $T_i^{(k)} = 1$, $\forall i$. We adopt it in this paper. We represent it as $A_i^{(k)}(t)$ (where t is the slot index in the k-th frame). We assume that it starts from 0, i.e., $A_i^{(1)}(1) = 0$, $\forall i \in \{1, 2, \ldots, N\}$, and for each slot in the frame, $A_i^{(k)}(t)$ increases by 1 (since the frame-based protocol performs SIC only at the end of the frame, it increases steadily within the frame). On the other hand, we denote the slot index sampled by U_i in the k-th frame as $T_i^{(k)}$, then a change [9] of it can be expressed as

$$A_i^{(k+1)}(1) = \begin{cases} A_i^{(k)}(M) + 1 & \text{if } U_i \text{ is not recovered at } M \\ M - T_i^{(k)} + 1 & \text{if } U_i \text{ is recovered at } M \end{cases} \tag{4}$$

Therefore, the AoI of U_i can be expressed as:

$$\bar{A}_i := \lim_{k \to \infty} \frac{1}{K} \sum_{k=1}^{K} \sum_{t=1}^{M} A_i^{(k)}(t) \tag{5}$$

When no update is successfully recovered, AoI increases linearly with time or slot, and AoI is calculated in units of frames. Thus, the AAoI of the system can be expressed as: $A = \frac{1}{N} \sum_{i=1}^{N} A_i$. The AoI sampling method that samples the AoI at the beginning of each frame is referred to as the "frame-based AoI sampling method". The slot index sampled by U_i in the k-th frame $T_i^{(k)}$ is a random variable that depends on the transmission strategy and the channel state. It represents when the receiver samples the AoI of U_i in each frame. The AoI evolution of U_i in the k-th frame $A_i^{(k)}(t)$ is a function that depends on the sampling method and the SIC process. It represents how the AoI of U_i changes over time or slots in each frame. The AAoI of the system A is a scalar value that depends on the transmission strategy, the collision resolution scheme, and the SIC process. It represents the long-term average AoI of all UE over many frames.

3 Age-Critical Access-Banned Policy

A frame-based protocol is a type of random access protocol that divides the time axis into frames, and each frame consists of a fixed number of slots. It can transmit one or more copies of its packet in each frame, and the BS can use SIC to decode the packets at the end of each frame. The advantage of a frame-based protocol is that it can reduce the decoding delay and improve the throughput by exploiting the diversity gain and the capture effect. However, a frame-based protocol also introduces a trade-off between the throughput and the AoI, since the AoI increases within each frame until a successful update is received. Therefore, it is important to design an optimal access strategy for UE to balance the trade-off and minimize the AAoI. In this paper, we consider the frame-based CRDSA protocol, which is a variant of the slotted ALOHA protocol that allows UE to transmit two copies of their packets in different slots within a frame. The CRDSA protocol can improve the collision resolution performance and increase the probability of successful decoding by SIC.

3.1 CRDSA Protocol

CRDSA protocols [12] let each user randomly select two slots in a MAC frame, and send the same packet in them, forming two replicas. They are both encoded by forward error correction, which can be used to recover lost or corrupted data. At the receiver, if there is one packet in a slot, it can be directly decoded. If there are multiple packets in a slot, a collision occurs, and SIC technique is needed to resolve it. The idea of SIC technique is to decode the strongest signal first, and then use it to cancel the interference in other signals, and then decode the next strongest signal, until all signals are decoded or no more interference cancellation is possible.

Here is an example to illustrate the principle of CRDSA: As shown in Table 1, suppose there are four users A, B, C, D who want to send packets. They randomly select two slots in a MAC frame to send the same packet in them, forming two replicas. They are both encoded by forward error correction, which can be used to recover lost or corrupted data. At the receiver, if there is one packet in a slot, it can be directly decoded. If there are multiple packets in a slot, a collision occurs, and interference cancellation is needed.

Table 1. Received signal collision decoding table

users/slot	1	2	3	4
A	A1	–	A2	–
B	B1	–	–	B2
C	–	C1	–	C2
D	–	–	D1	–

BS receives C1 and A2 in slot 2 and slot 3, respectively. They have no collisions and can be directly decoded. BS knows from the information of C1 and A2 that their other replicas are in slot 4 and slot 1, respectively. BS receives B2 and C2 in slot 4, which collide. BS first decodes the stronger signal C2, then uses C2 to cancel the interference in B2, and gets B2. BS receives A1 and B1 in slot 1, which collide. BS first decodes the stronger signal B1, then uses B1 to cancel the interference in A1, and gets A1. BS receives A2 and D2 in slot 3, which collide. BS first decodes the stronger signal A2, then uses A2 to cancel the interference in D1, and gets D1.

3.2 Access-Banned Policy

We consider some assumptions [8]: The UEs have unique IDs and can generate packets randomly according to a Bernoulli distribution with activation probability p. The BS can broadcast access parameters such as frame length, slot duration, and feedback information, and has a feedback channel to notify the UEs that their packets are successfully decoded in the current frame. The UEs adopt a frameless ALOHA protocol to transmit their packets in a grant-free manner, where each UE can choose two slots randomly and independently in each frame to send replicas of its packet. The BS can perform SIC to recover the collided packets in each slot, and can also exploit the time-stamp information in the packets to calculate the AoI of each UE.

The objective of access-banned policies is to calculate the AAoI of the UEs by preventing the transmission of the UEs that have been successfully decoded in the previous frame. The intuition behind this policy is that the UEs that have been decoded recently have lower AoI than the UEs that have not been decoded for a long time, and thus should give up their transmission opportunities to reduce the overall AAoI. The access-banned policy can be formulated as follows: At the beginning of each frame, each UE decides whether to activate or not according to the activation probability p, and its decoding status in the previous frame. If a UE was decoded successfully in the previous frame, it will not activate in the current frame; otherwise, it will activate with probability p If a UE is activated, it will generate a packet with a time-stamp indicating its generation time, and choose two slots randomly and independently in the current frame to send replicas of its packet. The BS will receive the packets from the UEs in each slot, and perform SIC to recover the collided packets. The BS will also broadcast a feedback message at the end of each frame, indicating which UEs have been decoded successfully in the current frame. The BS will calculate the AoI of each UE as the difference between the current time and the time-stamp of its latest decoded packet, and update the AAoI as the average of the AoIs of all UEs. The performance of the access-banned policy can be evaluated by analyzing the access success probability ASP stands for average successful packet rate, which is the ratio of the number of packets successfully decoded in a frame to the number of packets transmitted in a frame. The formula for ASP is

$$ASP = \frac{\mathbb{E}[N_R]}{\mathbb{E}[N_t]} \tag{6}$$

where $\mathbb{E}[N_R]$ represents the expected number of packets successfully decoded, and $\mathbb{E}[N_t]$ represents the expected number of packets transmitted.

The AAoI of the UEs under different system parameters, such as the activation probability p, the frame length M, and the number of UEs N. The ASP is defined as the probability that a UE is successfully decoded in a frame and can be derived using an iterative framework based on bipartite graph theory.

Our work is based on the access-banned strategy proposed by previous works [9], but it is the first to calculate the AAoI of the frame-based CRDSA protocol. The CRDSA protocol is a popular random access protocol for IoT devices as it can exploit the replicas of packets and the SIC technique to improve collision resolution performance and throughput.

We find that by banning the transmission of recently decoded UEs, we can effectively reduce the AAoI of the UEs in the system and enhance the reliability and efficiency of the system. Compared with other age-critical random access protocols, our strategy does not require any explicit feedback or coordination among the UEs and only relies on a simple rule and the broadcast information from the BS. This makes our strategy more suitable for grant-free massive access scenarios where feedback overhead and coordination complexity should be minimized.

3.3 ASP and AAoI Performance

We can model the system of CRDSA as a bipartite graph [13], which is a graph whose vertices can be divided into two disjoint sets, such that every edge connects a vertex from one set to another. In this case, the two sets are the user nodes and the slot nodes, and an edge represents a replica of a packet. Then we can use graph theory methods to analyze the performance of CRDSA.

(1) We define a bipartite graph $G = (B, S, E)$, where B is the set of user nodes, S is the set of slot nodes, and E is the set of edges. Each edge has two endpoints that belong to the sets B and S, respectively. Therefore, an edge corresponds to a replica of a packet.

(2) We define a slot node as clean, according to the SIC algorithm, if it has only one edge connected to a user node. Then, this user node can be successfully decoded, and it can eliminate the interference on the other slot nodes that it is connected to.

(3) We define a slot node as active if it has at least one edge connected to a user node. Then, this slot node can be used for the SIC process. We define a slot node as dead if it has no edges connected to any user nodes. Then, this slot node cannot be used for the SIC process.

(4) We define a user node as active if it has at least one edge connected to a slot node. Then, this user node has a chance to be successfully decoded. We define a user node as dead if it has no edges connected to any slot nodes. Then, this user node cannot be successfully decoded.

(5) We use $\rho(G)$ to denote the spectral radius of the bipartite graph G, which is the absolute value of the largest eigenvalue of its adjacency matrix. We use $\lambda(G)$ to denote the largest eigenvalue of the bipartite graph G. We use $\mu(G)$ to denote the smallest eigenvalue of the bipartite graph G.

(6) Define the packet recovery rate (PRR) as the ratio of the number of successfully decoded packets to the number of transmitted packets. We can write PRR as $PRR = \frac{N_R}{N_a}$, where N_R is the number of successfully decoded packets, and N_a is the number of transmitted packets.

(7) To calculate N_R, we need to count the number of clean slot nodes in the bipartite graph G, since each clean slot node corresponds to a successfully decoded packet. We can use a theorem from graph theory that states that the expected number of clean slot nodes in a regular bipartite graph is equal to $E[N_C] = \frac{M}{\rho(G)}$, where M is the number of slot nodes, and $\rho(G)$ is the spectral radius of G.

(8) To calculate N_a, we need to count the number of active user nodes in the bipartite graph G, since each active user node corresponds to a transmitted packet. We can use another theorem from graph theory that states that the expected number of active user nodes in a regular bipartite graph is equal to $E[N_a] = N(1 - e^{-\lambda(G)})$, where N is the total number of user nodes, and $\lambda(G)$ is the largest eigenvalue of G.

(9) Therefore, we can write PRR as

$$PRR = \frac{E\left[N_C\right]}{E\left[N_a\right]} = \frac{M}{N\rho\left(G\right)} \cdot \frac{1}{1-e^{-\lambda(G)}} \tag{7}$$

We first assume that each UE has the same activation probability and access probability in each frame, and each UE has the same successful decoding probability in each frame, and each UE has the same sampling slot index in each frame. These assumptions are valid based on the sparse access model and the sampling strategy starting from the first time slot.

The sparse access model is a model that assumes that the number of packets transmitted is much smaller than the number of slots, which is suitable for bursty and sporadic traffic. The asymptotic ASP is the value that the ASP converges to when the number of users N tends to infinity. The iterative method is a numerical method to solve the asymptotic ASP, which uses the following steps:

Define η as the ratio of the total number of active users N to the frame length M, i.e., $\eta = \frac{N}{M}$. According to formula (7), we can see that PRR is a function of η. The initial value of the iteration variable x is p_a, i.e., $x^{(1)} = p_a$, where p_a is the average activity of the user nodes, which indicates how many user nodes transmit packets in a frame.

Using the fixed-point iteration method, $x^{(k+1)} = \psi(x^{(k)})$, where $\psi(x) = p_a(1 - xf(\eta x))$, $f(\eta x)$ is the PRR formula of the protocol, which indicates the ratio of the number of packets successfully decoded in a frame to the number of packets transmitted in a frame. The final expression of ASP is $P_{\text{ASP}} = \lim_{k\to\infty} f(\eta x^{(k)})$.

Finally, let's provide the reasoning for the AAoI expression of CRDSA with access prohibition in the sparse access model under the first slot sampling method:

According to the principle of CRDSA, each UE transmits two replica packets in each frame, each replica packet occupies one slot, and the slot selection is random and uniform.

According to the binomial distribution, we can calculate the probability of each slot being occupied or idle, as well as the probability of each slot being occupied once or multiple times. Let X be the number of times a slot is occupied, then X follows a binomial distribution with parameters $2NP_{\text{ASP}}$ and M, i.e., $X \sim B(2NP_{\text{ASP}}, M)$. $Pr(X > 1) = 1 - (1 - 2NP_{\text{ASP}})^M - 2MP_{\text{ASP}}(1 - 2NP_{\text{ASP}})^{M-1}$ is the probability of a slot being occupied multiple times.

Then, according to the interference cancellation technique, we can calculate the probability of each slot being successfully decoded or undecoded, as well as the probability of each frame being successfully decoded or undecoded. Let Y be the number of times a slot is successfully decoded, then Y follows a binomial distribution with parameters X and p_d, i.e., $Y|X = x \sim B(x, p_d)$, where p_d is the probability of a slot being successfully decoded, which depends on the signal-to-noise ratio and the modulation and coding scheme, determined by the link adaptation technique.

According to the total probability formula, we can get $Pr(Y = 0) = Pr(Y = 0|X = 0)Pr(X = 0) + Pr(Y = 0|X = 1)Pr(X = 1) + Pr(Y = 0|X > 1)Pr(X >

$1) = (1-p_d)Pr(X=1)+Pr(X>1)$, which is the probability of a slot not being successfully decoded. $Pr(Y=1) = Pr(Y=1|X=0)Pr(X=0) + Pr(Y=1|X=1)Pr(X=1) + Pr(Y=1|X>1)Pr(X>1) = p_d Pr(X=1)$ is the probability of a slot being successfully decoded.

Let Z be the number of times a frame is successfully decoded, then Z follows a binomial distribution with parameters M and $Pr(Y=1)$, i.e., $Z \sim B(M, Pr(Y=1))$. $Pr(Z>0) = 1 - Pr(Z=0) = 1-(1-Pr(Y=1))^M$ is the probability of a frame being successfully decoded.

Finally, according to the impact of successful decoding and failed decoding on AoI, we can calculate the AAoI of each UE and the whole system. Let V be the number of times a UE is successfully decoded in a frame, then the probability of a UE being successfully decoded is $\Pr(V>0) = \Pr(Z>0)^2 {P_{ASP}}^2$. According to the definition of AoI, we can get the AAoI of each UE as

$$AAoI_{CRDSA} = \frac{\sum_{k=1}^{\infty} kM(1-Pr(V>0))}{\sum_{k=1}^{\infty}(k-1)Pr(V>0)} + \frac{M}{2} + \frac{1}{2} \tag{8}$$

Finally simplify to get

$$AAoI_{CRDSA} = \frac{M}{N}\left(\frac{1}{{P_{ASP}}^2} - \frac{1}{P_{ASP}}\right) + \frac{M}{2} + \frac{1}{2} \tag{9}$$

where, the first term represents the AoI accumulated by each UE between each successful decoding, the second term represents the AoI reset by each UE after each successful decoding, and the third term represents the average increase in AoI within each slot.

4 Simulation Results and Analysis

In this section, we validate our analysis through simulations. The specific parameters are set as shown in Table 2.

Table 2. Simulation parameter settings

Parameters	Value
Number of UEs N	2000
Number of slots K	[2, 10]
Frame Length M	[50, 200]
Active Probability p_a	0.3251
SIC Maximum Iterations	10
Path Loss Exponent	4

Figure 3 shows the changes of AAOI of two algorithms at different frame lengths. The AAOI of both Proposed Algorithm and CRDSA increases as the

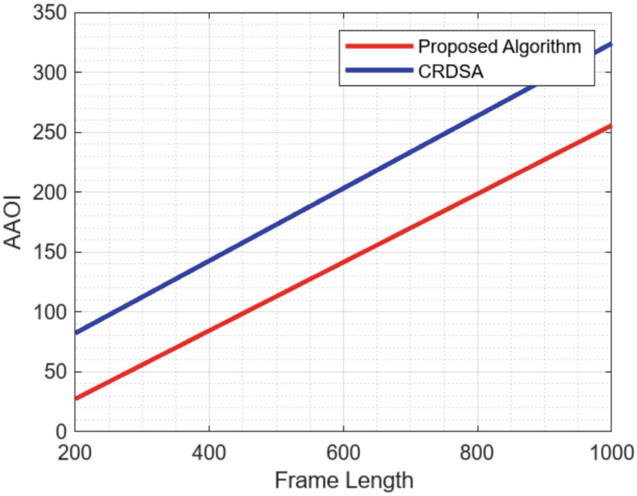

Fig. 3. Changes in AAOI with different frame lengths

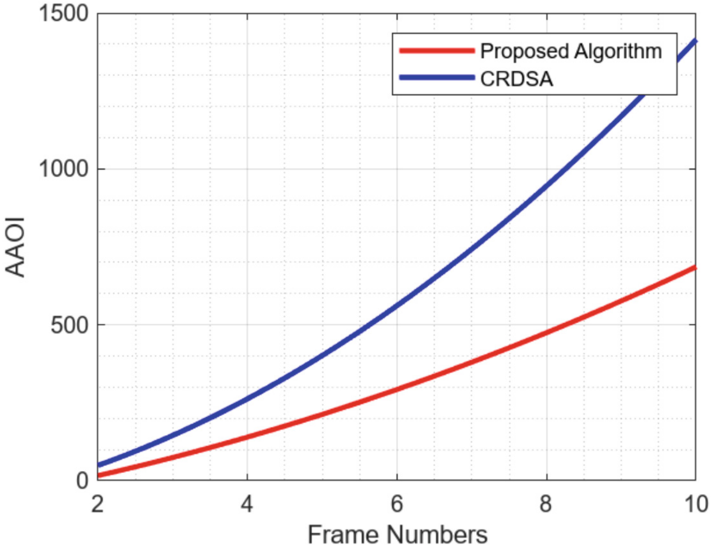

Fig. 4. Changes in AAOI with different frame numbers

frame length increases, indicating that the information timeliness decreases as the frame length becomes larger. The AAOI of Proposed Algorithm is lower than that of CRDSA at all frame lengths, indicating that Proposed Algorithm can better guarantee the information timeliness than CRDSA.

Figure 4 shows the changes of AAOI of two algorithms at different frame numbers. The AAOI of both Proposed Algorithm and CRDSA increases as the frame number increases, indicating that the information timeliness decreases as the frame number becomes larger.

The AAOI of Proposed Algorithm is lower than that of CRDSA at all frame numbers, indicating that Proposed Algorithm can better guarantee the information timeliness than CRDSA. Proposed Algorithm has a faster decline of information timeliness at low frame numbers, but a slower decline of information timeliness at high frame numbers.

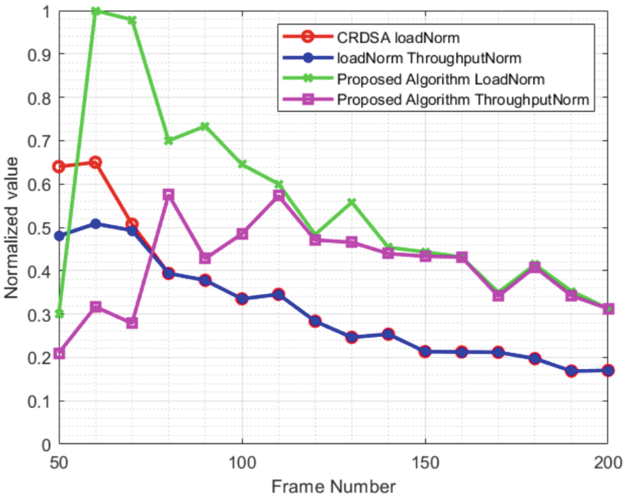

Fig. 5. Normalized load and throughput vary with frame length

Figure 5 shows the normalization values of both algorithms decrease with the increase of frame length, but the proposed algorithm has a smaller decrease, indicating that they are more suitable for different frame lengths. The proposed algorithm has higher load and throughput than the CRDSA algorithm, indicating that they more effectively utilize channel resources and improve network performance. The small difference between the load and throughput of the proposed algorithms indicates that they allocate channel resources more evenly, avoiding situations of overload or underload. The significant difference between the load and throughput of CRDSA algorithms indicates that they have certain resource waste or congestion issues, which affect network performance.

Figure 6 shows the normalization values of both algorithms fluctuate as the number of frames numbers, but the fluctuation amplitude of the proposed algorithm is smaller, indicating that they are more stable. The proposed algorithm has higher load and throughput than the CRDSA algorithm, indicating that they more effectively utilize channel resources and improve network performance. The significant difference between the load and throughput of the proposed algorithms indicates that they have certain trade-offs or trade-offs that need to be adjusted according to different scenarios. The small difference between the load

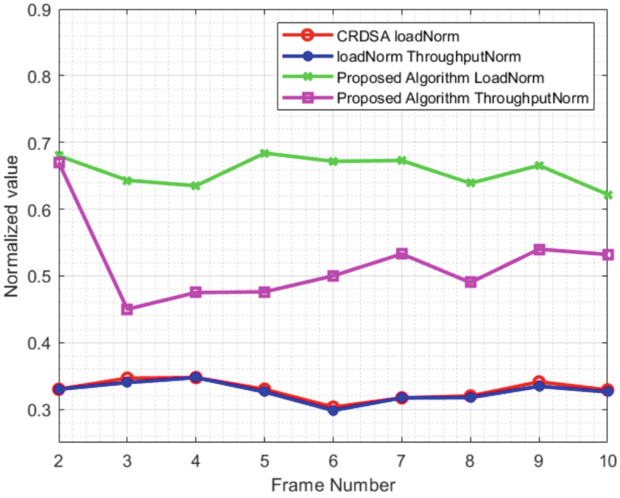

Fig. 6. Normalized load and throughput vary with frame numbers

and throughput of the CRDSA algorithm indicates that they allocate channel resources more evenly, but their overall performance is low.

5 Conclusion

In conclusion, this study made significant contributions to the analysis and optimization of the frame-based CRDSA protocol in a synchronous slot-based uplink random access system. By introducing an access-banned policy, the AAoI was effectively minimized, leading to improved system performance. The research involved modeling the CRDSA system as a bipartite graph, allowing for the application of graph theory methods to analyze its performance. The access-banned policy, which prevents recently decoded users from transmitting in the current frame, was proposed as a simple yet effective strategy to reduce the AAoI. This policy leverages the insight that recently decoded users have lower age of information and should yield their transmission opportunities to enhance overall system efficiency. Through extensive analysis, the study derived expressions for the ASP and AAoI of the system. The asymptotic ASP was calculated using an iterative framework based on bipartite graph theory, providing valuable insights into the system's throughput. Moreover, the impact of successful and failed decoding on the age of information was considered, resulting in an expression for the AAoI of each user and the overall system. The results demonstrated the effectiveness of the proposed access-banned policy in reducing the AAoI in the frame-based CRDSA protocol. The analysis and derived expressions offer a deeper understanding of the trade-off between throughput and age of information in such communication systems. This research contributes to the optimization and design of CRDSA protocols, particularly in the context of IoT scenarios with massive access.

Future research endeavors could explore more advanced access-banned policies, investigate different traffic patterns, and explore alternative metrics for evaluating system performance. The proposed framework lays a solid foundation for further studies on the design and optimization of random access protocols across diverse communication systems.

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